X-625-71-34
PREPRINT

TM X-65445

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EDWARD P. SZUSZCZEWICZ

JANUARY 1971

GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

ION-CURRENT RESPONSE OF LANGMUIR PROBES IN THE PRESENCE OF ION-ATOM COLLISIONS

by

Edward P. Szuszczewicz*
Laboratory for Planetary Atmospheres
NASA/Goddard Space Flight Center
Greenbelt, Maryland

ABSTRACT

The analysis of the Langmuir probe experiments of Szuszczewicz and Weber is extended to present a more quantitative description of the effects of ion-atom collisions on the ion saturation current of a probe characteristic. The experiments were conducted with cylindrical probes of length-to-diameter ratios in the range $30 < L/d < 120$. The probes were studied in a weakly ionized argon plasma with conditions such that $0.7 < N_e(\mathrm{x}10^{-8}\mathrm{cm}^3) < 5.0$, $R_p/\lambda_D < 1$, and $3 < \lambda_{ia}/R_p < 500$, where N_e is defined as the undisturbed electron number density, R_p the probe radius, λ_D the Debye length, and λ_{ia} the ion-atom mean free path. The experimental results show that the ion-saturation current is an increasing function of λ_{ia}/R_p with the level at $\lambda_{ia}/R_p = 4$ approximately equal to 50% of that which is observed in the collision-free limit and that absolute collision-free behavior is not achieved until $\lambda_{ia}/R_p \sim 400$. A comparison of the experimental results with the approximate theoretical analysis of Talbot and Chou shows good agreement.

*NRC Resident Research Associate

INTRODUCTION

Recent investigations on cylindrical Langmuir probes have shown a considerable influence of particle collisions on the response of a probe operating in the transition and near collision-free regime.[1,2] The experimental work has been primarily conducted under conditions for which $R_p/\lambda_D > 2$, where R_p is the probe radius and λ_D is the electron Debye length. The purpose of the present study is to extend the analysis of the experiments of Szuszczewicz and Weber[3] in order to present a more quantitative description of the effects of ion-atom collisions on the ion-saturation currents collected by cylindrical Langmuir probes when $R_p/\lambda_D < 2$ and to compare the experimental results with the approximate theoretical analysis of Talbot and Chou.[2]

THE EXPERIMENT

The experiment discussed here was originally reported by Szuszczewicz and Weber[3] in connection with the discrepancies between the experimental results of Sonin[4] and Bell[5] and the theoretical work of Laframboise[6] on cylindrical Langmuir probes. The availability of the theoretical analysis of Talbot and Chou[2] as presented by Kirchhoff, Peterson and Talbot[1] on the influence of ion-atom collisions on cylindrical Langmuir probe response now permits a more quantitative discussion of their original work (Ref. 3) and makes possible a more complete understanding of Langmuir probe response for small values R_p/λ_D.

The experiment was conducted in an argon plasma with conditions such that $7(10^7)/\text{cm}^3 \leq N_e \leq 5(10^8)/\text{cm}^3$, $< T_e/T_i > = 5$ and $4 \lesssim \lambda_{ia}/R_p \lesssim 500$. N_e is the undisturbed electron number density, T_e and T_i are the electron and ion temperatures respectively, and λ_{ia} is the ion-atom mean free path. The probes employed were constructed by permitting a length of pure tungsten wire to protrude from Pyrex tubing which was drawn to a fine diameter. The diameters of the probes were in the range of 0.07 mm to 0.51 mm and the ratios of length-to-diameter varied between 30 and 120.

For a given plasma condition two successive Langmuir probe characteristics were collected at the same point in the plasma with two probes of different radii. This made possible the determination of the relative behavior of ion-saturation currents as a function of ion-atom mean free paths, λ_{ia}, which could then be presented as a plot of dimensionless ion-current $I_i(\chi_f-10)$, defined by Eq. (1), versus λ_{ia}/R_p.

$$I_i(\chi_f-10) = (1/n_e e)\ (2\pi M/kT_e)^{1/2}\ j_i(\chi_f-10) \tag{1}$$

In Eq. (1) $n_e e$ is the undisturbed volume charge density of plasma electrons, M is the ion mass, T_e is the electron temperature and $j_i(\chi_f-10)$ is the experimentally observed ion-current density collected by the probe at a potential which is 10 kT_e/e volts negative with respect to the floating potential. χ_f is the probe's floating potential referenced to the plasma potential and normalized to kT_e.

A probe traversing mechanism permitted proper positioning of probes and a probe-probe separation of approximately 18 cm whenever a given probe was active. (An active probe is defined as one to which voltages are applied in such a way as to collect a full current-voltage characteristic). The active probe was always on the axis of symmetry of the plasma volume, while the inactive probe was maintained at ground potential near the wall of the vacuum chamber. For a constant set of values for n_e, T_e, and λ_{ia} a given pair of current-voltage characteristics was analyzed and the relative behavior of $I_i(\chi_f-10)$ established as a function of λ_{ia}/R_p. The ion-atom mean-free-path was calculated from Eq. (2)

$$\lambda_{ia} = 1/\sqrt{2}\, n\, Q_{ia} \tag{2}$$

where n is the atomic number density and Q_{ia} is the corresponding cross-section which was taken from Wobschall, Graham and Malone[7] as 215 $\pm$ 40 $\mathring{A}^2$. The method for calculating λ_{ii} was taken from Sonin[8] and in every case it was found that $\lambda_{ii} >> \lambda_{ia}$.

A series of data pairs was collected employing different probes and different conditions of n_e, T_e and λ_{ia}. The experimental results (shown in Fig. 1) were plotted by defining the value of $I_i(\chi_f-10)$ corresponding to $(\lambda_{ia}/R_p)_{max}$ to be equal to unity. The values of I_i which conform to this definition are here referred to as I_i^* and are plotted as such. The reasons for this definition

will be discussed in connection with the comparison between theory and experiment. Data pairs were arranged in such a way that abscissa values overlapped, thus making possible the use of interpolation to determine I_i^* for the smaller probe in a given data pair. This procedure is in principle the "bootstrap" technique previously described by Sonin[4,8]. The error bars in the bascissa values represents the accuracy in the values of λ_{ia} as determined by the collision cross-section reported by Wobschall, et al[7]. In all cases the data points represent more than a single measurement with the vertical error bars indicating the spread in I_i^* values.

DISCUSSION

The experimental results show that the ion-saturation current is an increasing function of λ_{ia}/R_p with the level at $\lambda_{ia}/R_p = 4$ approximately equal to 50% of that which is observed in the collision-free limit. The results also show that absolute collision-free behavior is not achieved until $\lambda_{ia}/R_p \sim 400$ and that the approach to this limit is asymptotic for large values of λ_{ia}/R_p.

For purposes of comparison Fig. 1 includes the results of the approximate theoretical analysis of Talbot and Chou[2] as taken from Kirchhoff, Peterson and Talbot[1] for the conditions $R_p/\lambda_D \lesssim 2$ and $T_e/T_i = 10$. The value of I_i in the collisionless limit was taken by Talbot and Chou[2] from the theoretical work of Laframboise[6] and is here defined as unity. The theoretical curve applies to a probe with an

actual aspect ratio of 100, that is $L/R_pX_o = 100$ where L is the probe length and X_o is the dimensionless ion sheath radius. The dimensions of the probes employed in the experiment were such that $64 \leq L/R_p \leq 240$ and the plasma conditions yielded values of X_o of the order 10. Consequently the experimental values for the actual aspect ratios are quite small. The absolute value of I_i for probes of low aspect ratio operating in the collisionless regime is expected to be between the value for an infinite cylinder and that for a sphere. It is therefore the intent of the definition, $I_i = I_i^* \equiv 1$ for very large λ_{ia}/R_p, to achieve a comparison between the experiment and theory in a relative fashion. It can be seen that the experimental results of this investigation for the dependence of $I_i^*(\chi_f-10)$ on λ_{ia}/R_p are in relatively good agreement with the analysis of Talbot and Chou.[2] Quantitatively however, the experimental curve yields lower values of I_i^* for a given λ_{ia}/R_p with a maximum difference of about 10-15% below the theoretically predicted value when $\lambda_{ia}/R_p < 30$.

From the experimental point of view, a larger value for Q_{ia} would yield correspondingly smaller values of λ_{ia} with a resulting better agreement with theory. However, there is no reason to suspect that the value of Q_{ia} as reported by Wobschall, et al.[7] is too small. The latter authors used the ion-cyclotron resonance absorption line-width to determine the ion-atom collision cross section and

their results are in agreement with previously reported values determined by mobility measurements.

It is believed that the difference is largely a result of the fact that the actual aspect ratio of the probe in the theoretical analysis is 100 while in the experiment it is estimated that the ratio varied approximately between 6 and 24.

SUMMARY

An experimental study of the effects of ion-atom collisions on the ion-saturation current to a cylindrical Langmuir probe has been carried out in the region $R_p/\lambda_D < 1$ with the results demonstrating that the ion-saturation current decreases as λ_{ia}/R_p decreases.

The results provide a quantitative guideline to the influence of collisions on the response of Langmuir probes with low aspect ratios and the agreement with theory indicates that the influence of collisions on ellipsoidal-like probes (i.e. probes with small aspect ratios) is very similar to that for perfect cylinders.

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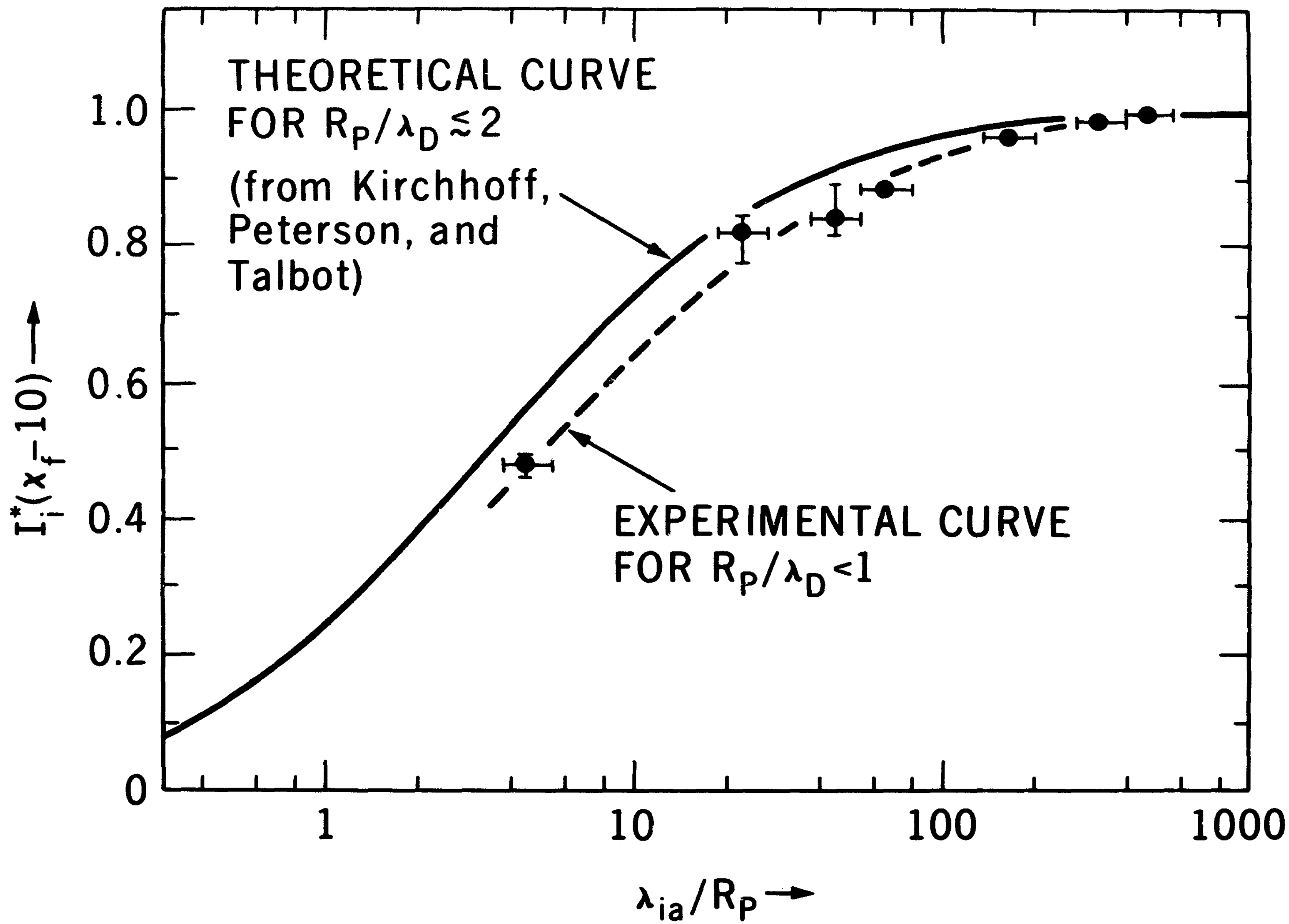

Fig. 1. Experimental variation of the dimensionless ion current, I_i^*, with the Knudsen number, λ_{ia}/R_p, compared with the theoretical results of Talbot and Chou [in Rarefield Gas Dynamics (C.L. Brundin, ed). Academic Press. New York (1969). Vol. II, pp. 1723-1737] as taken from Kirchhoff, Peterson and Talbot [AIAA Paper No. 70-85, New York (Jan. 1970)].